REAL TIME MONITORING OF SUBSIDENCE OVER AN INACTIVE MINE IN VIRGINIA USING TDR

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ABSTRACT

Closure activities at the USG facility in Plasterco, Virginia include realignment of an existing highway outside the predicted limits of long term subsidence. Concerns about the possibility of subsidence along the highway being induced by construction activities, or in the former plant area where excavated rock is being placed, motivated the installation of a real time monitoring system. Rapid development of sinkhole features is of particular concern because they can pose nearly non-predictable and sudden safety hazards. The goal at Plasterco is to provide an early warning system for catastrophic subsidence.

Time Domain Reflectometry (TDR) involves electrically interrogating coaxial cables that are grouted into drill holes and trenches. This technology can be used to determine the location and rate of precursor subsurface movement that is occurring. The sensitivity of TDR to rock mass movement is related to the proximity of cable installations to subsiding ground. The lateral extent of monitoring is enhanced by installation of cables in trenches over a wide area, and the depth of monitoring is enhanced by installation of cables in deep vertical or angled holes beneath critical structures.

Manual monitoring of three cables began in June 2001. Since then, the system has been expanded to automated real time monitoring of 21 cables with lengths that vary from 10 m (30 ft) to 270 m (886 ft) for a total of over 2500 m (8200 ft) of cable. They are installed in angled holes beneath the existing highway, in trenches along the highway, and in trenches over the former plant area where rock excavated for the new alignment is being placed. The automated monitoring incorporates a call back capability. Whenever the difference between the baseline profile and the current profile at any location along a cable exceeds a preset alarm threshold, the datalogger will initiate a call to responsible personnel.

BACKGROUND

Site Location

The United States Gypsum Company (USG) Plasterco project site is located in Washington County in southwestern Virginia near the town of Saltville. The site is within a narrow valley that is part of the larger Valley and Ridge province of the southern Appalachian Highlands (Figure 1). This region is typified by rugged, linear, northeast-trending ridges separated by relatively narrow valleys. Topographic relief around the general project site is about 100 m (300 feet). The dominant geomorphologic processes affecting the area are karst, shale slumping and mining-related subsidence. Perennial streams crossing the project site are McHenry Creek and Keywood Branch.

Underground mining of gypsum is reported to have occurred at Plasterco beginning in the late 1800's, although surface quarries were worked earlier *(1)*. The Buena Vista Plaster Company began operating gypsum quarries and plaster works at Plasterco in 1808 *(2)*. The Smith family and descendents operated the Buena Vista gypsum and plaster works more or less continuously from that time until 1907. USG leased the Buena Vista operation in 1909 and purchased it in 1923. The mine was operated by USG from 1911 to 1979, at which time it was the deepest gypsum mine in the world. The underground workings have a strike length of more than 3,600 m (12,000 feet). The mine was worked on 16 levels with the deepest at 430 m (1,420 feet) below the main shaft collar.

Figure 1 View looking northeast over the former board plant area. SR91 is at the base of the hill on the right side.

After cessation of underground mining at Plasterco, the wallboard plant continued production with gypsum supplied from another mine until 1999. The plant was dismantled in 2000. The main plant building and support facilities site covered an area of 100 acres that remains extensively undermined (Figure 1). State Route 91 and County Road 745 are located on the southeast margin of the site and are undermined or near mapped underground workings (to the right in Figure 1). These highways are strategically important as transportation arteries in this area for automobiles, trucks, and school buses. Consequently, keeping these roads open is a critical issue.

Geological Setting and Historical Subsidence

The geological conditions at Plasterco consist of three major features shown in Figure 2: 1) the Greendale Syncline, 2), the Mississippian-age Maccrady Formation which contains gypsum deposits, and 3) the Saltville Thrust Fault. The unique combination of structural and stratigraphic features in this area resulted in the concentration of mineable deposits of gypsum.

Mining in the Maccrady Formation was done within two distinct gypsum-bearing zones (Figure 2). The "boulder" zone consists of erratic, discontinuous gypsum lenses that are encapsulated in marine mudstone. The "footwall" zone is a discrete gypsum seam lying stratigraphically above the boulder zone and conforms to the east limb of the Greendale Syncline. Both occurrences of gypsum were mined by overhand stoping methods with sublevel haulage ways connecting the mining areas. Some resulting stopes (i.e., openings) were 100 m (300 ft) long and 30 m (100 ft) high.

Within the Maccrady Formation the strongest rock in terms of load-bearing capacity is the gypsum. As the gypsum was mined, ground support was provided predominately by the remaining weaker mudstones. In particular, the surface crown pillars over the mine openings are dominantly mudstones.

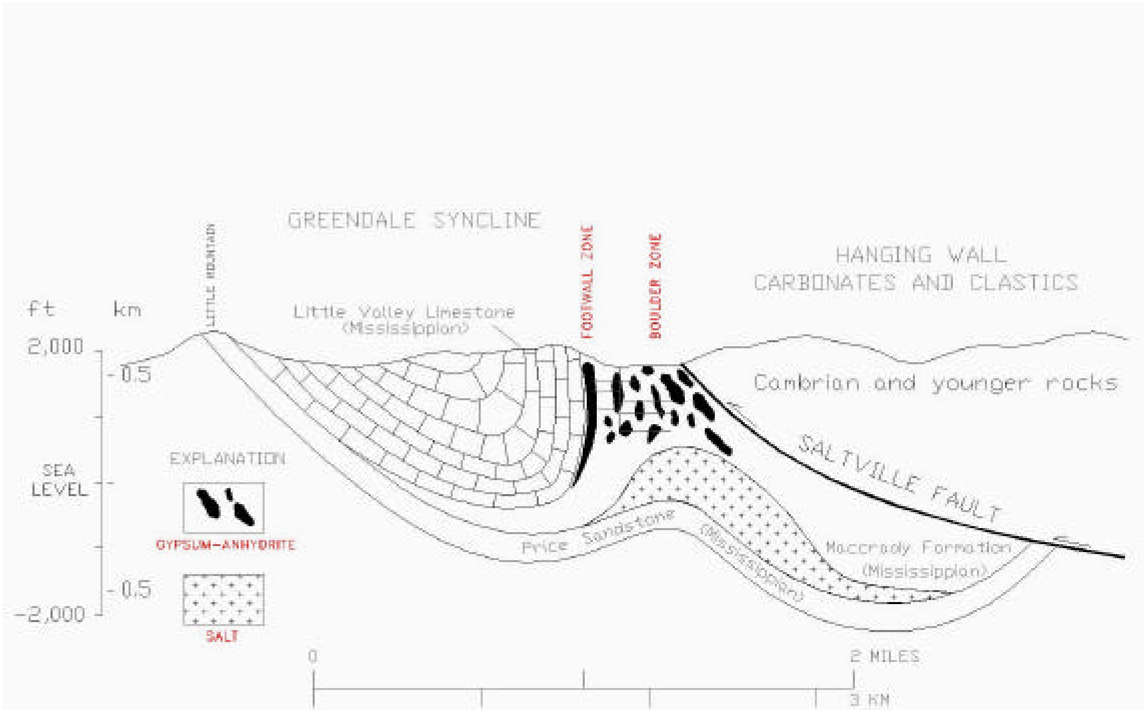

Figure 2 Schematic of geologic setting looking northeast.

USG has taken the position that the Maccrady Formation in the mined area has marginal self-supporting capacity, based on rock strength analyses and geological conditions. Compressive and shear strength of the Maccrady mudstones will degrade over protracted time periods. Sloughing and collapse of Maccrady Formation mudstone support structures into mined voids upon wetting has been experienced at Plasterco. This has resulted in the formation of surface subsidence features. The sloughing of the mudstones into flooded mine voids generally overrides any benefits of mine water pressure providing ground support. For this reason, the mine water pool level is being maintained down into the deeper mine levels by continuous pumping until final mine closure begins. Furthermore, the two perennial streams crossing the undermined portion of the property have been lined to reduce additional water inflow.

There are about 60 mining-related subsidence sinkholes that have developed across the property since 1911. The sinkholes varied from 15 m to 150 m (50 to 500 feet) in diameter and from 1 m to 25 m (3 to 75 feet) in depth. About 12 of these sinkholes have occasionally reactivated many years after initial remediation by backfilling. For example, a large sinkhole developed beneath SR91 in 1936 and was reactivated in 1977.

Mine Closure Activity

The mine closure plan consists of several components that anticipate flooding of the mine workings and resultant subsidence. These include fencing the mine property, backfilling of mined voids, and relocating SR 91 and CR 745. Backfilling by hydraulic and pneumatic stowage of various materials has been ongoing since the early 1980's. Holes have been drilled to introduce fill into selected stopes. The level of fill is monitored using optical or mechanical devices, and it has been determined that backfill placed in shallow stopes can move to deeper mine levels over time.

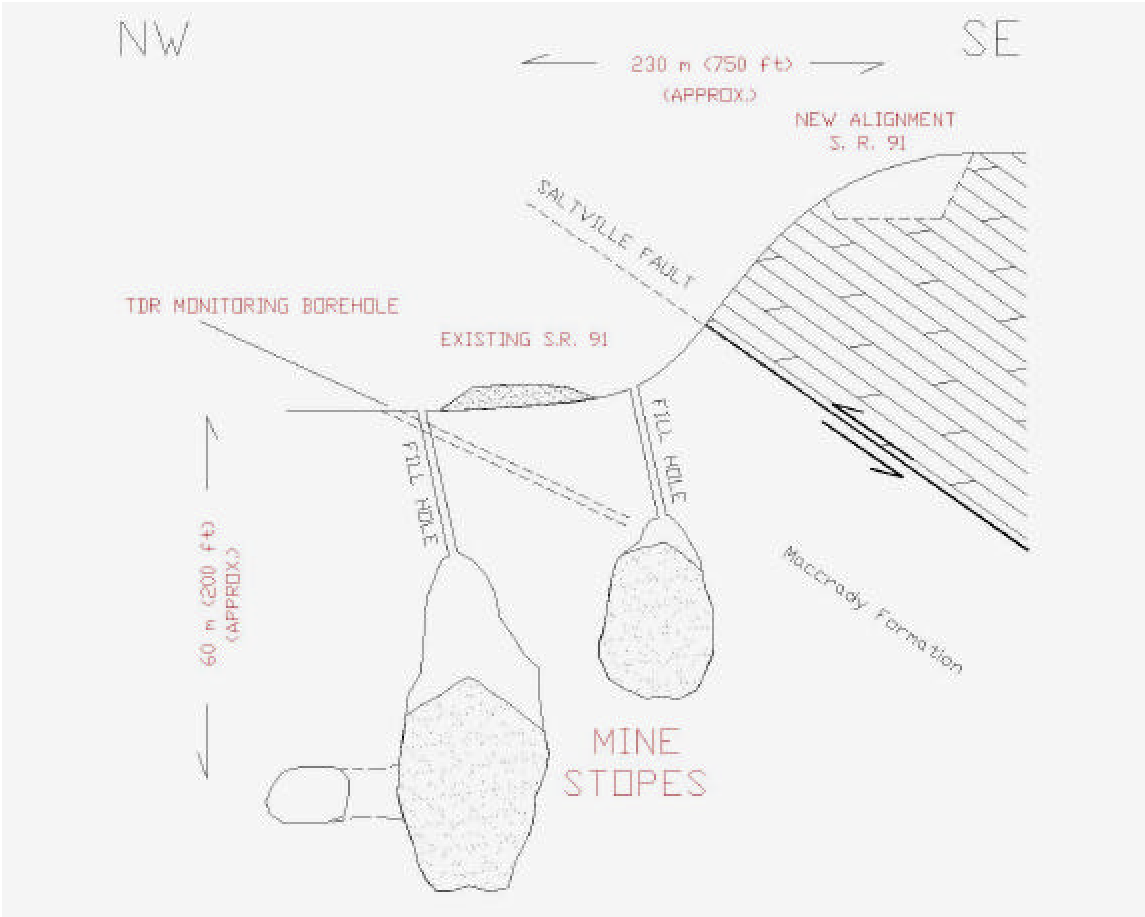

Figure 3 Cross section across S.R. 91 looking northeast.

A fundamental understanding of contributing factors, such as hydrogeology and its effect on rock strength, were researched while developing the closure plan. When pumping of mine water is stopped and water levels rise, it is expected that subsidence will occur. In anticipation of this subsidence, USG is relocating a portion of SR 91 to place it in a "least-impact" alignment such that (a) there is a minimum of mined voids directly beneath the proposed alignment and (b) construction does not require destroying cultural features.

The present location of the road is adjacent to and overlies old mine workings, including drifts and stopes. Mine workings as shallow as 15 m (50 ft) below the surface in at least one location (Figure 3). The relocation will involve construction of a new portion of highway several hundred meters east of its present location (Figure 4). In addition, the new alignment is situated at a higher elevation on a massive, rigid beam of limestone that is an upthrown fault block above the detachment surface of the Saltville Thrust Fault (Figure 3). This, in effect, places the road along structurally strong ground that is also vertically separated from the weaker Maccrady mudstones. An extensive coring and laboratory test program was conducted for geotechnical evaluation prior to final alignment selection. Relocation of the highway alignment will require a rock cut about 60 m (200 ft) high. This involves blasting and removal of about 1.0 million m^3 of limestone and/or dolomite. The excavated rock is being hauled across the mine workings and placed as rock fill over the former wallboard plant site (Figures 1 and 4).

Relocation of CR 745 will proceed in a manner similar to SR 91, and has comparable geology. However, the mine openings near CR 745 are generally deeper and farther west of the current alignment compared with mine openings near SR-91.

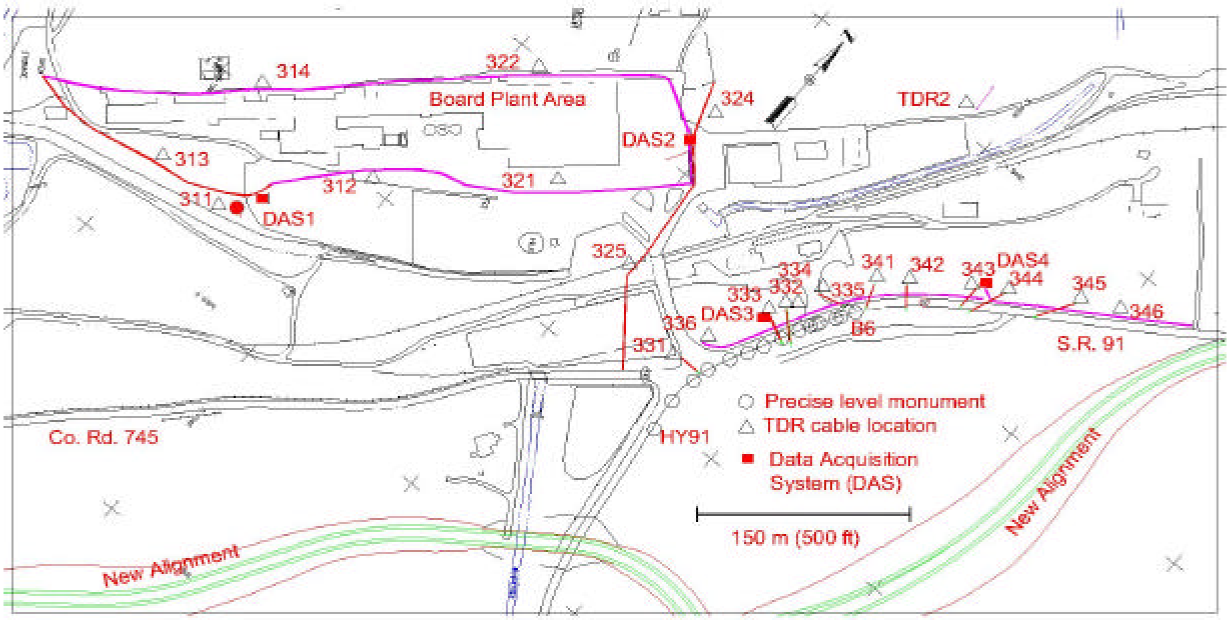

Figure 4 Site plan showing highway realignment and monitoring locations

TABLE 1 Installation Summary

	Cable ID		Lead cable length (m)	Sensor cable length (m)	Comments
DAS1	311	*	30	46	Vertical hole – shaft area
	312	*	15	154	Trench in board plant / fill area
	313			200	“
	314	*	200	247	
DAS2	321	*	41	152	“
	322	*	8	246	“
	323			7	Test line
	324			63	Trench along haul road
	325			186	“
DAS3	331	*	82	27	Angled hole beneath SR91
	332	*		115	“
	333		5	33	“
	334			36	“
	335			272	Trench along SR91
	336		45	56	Angled hole beneath SR91
DAS4	341		58	57	“
	342	*	58	41	“
	343		8	50	“
	344	*	15	43	“
	345	*	76	38	“
	346	*		159	Trench along SR91

NOTE: * Indicates cables where movement has been detected as of 10/24/03

Monitoring Subsidence

Public safety and contractor safety are critical components of the mine closure plan. The objective is to monitor the stability of the main construction areas during construction and also during post-construction flooding of the mine. USG personnel with extensive knowledge of mine operations and historic subsidence activity selected three areas for intensive monitoring. The sites were selected based upon previous subsidence, depths and dimensions of mine stopes, and an empirical assessment of the potential for subsidence. These areas include (a) the SR 91 right-of-way, (b) the former wallboard plant area, and (c) construction haulage roads (Table 1).

The monitoring program is designed to encompass the immediate and long-term aspects of mine closure activities. For example, one concern is the immediate impact of construction blasting on the stability of the underground workings in proximity to the existing roadway. During blasting, S.R. 91 is closed temporarily. Otherwise, the road is kept open and TDR is used to monitor ground movements underneath and adjacent to the highway.

Precise level subsidence monitoring has been performed since the mid-1980's and will continue during mine closure. Water levels inside the mine are monitored continuously with a call back alarm capability to alert responsible personnel when power to the pumps is disrupted. In the event that power is disrupted, standby generators are available. After mine closure, long-term monitoring of (a) subsurface movement, (b) mine water levels, and (c) surface stream water levels will be maintained.

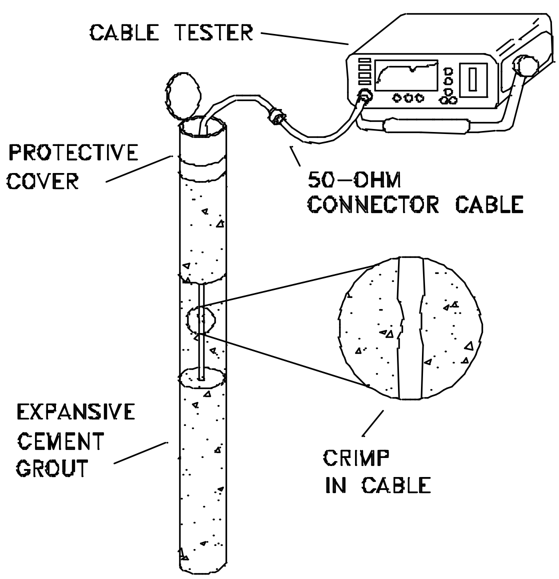

Figure 5 Schematic of TDR cable installation in vertical borehole.

TDR OPERATING PRINCIPLE

Time Domain Reflectometry (TDR) is a form of RADAR in which voltage pulses are transmitted along coaxial cable, and reflections are created at every location where the cable is deformed such as the crimp shown in Figure 5. The distance to each location is determined by the pulse travel time, and the magnitude of deformation at each location is determined by the magnitude of its TDR reflection *(3)*. The basic hardware consists of a coaxial cable embedded in the ground being monitored and a TDR cable tester to interrogate the cable. Cable in use for TDR monitoring at Plasterco is CommScope Parameter III solid aluminum 22.2 mm (7/8 in.) diameter coaxial cable. Prior to installation, the cable is crimped as shown in Figure 5 to provide reference reflections at known physical locations.

In vertical and inclined installations, the crimped cable is lowered down a borehole and bonded to the surrounding rock with an expansive cement grout that is tremied into the hole. In trench installations, the cable is placed along the bottom of the trench (typically 1 m (3 ft) deep) and bonded to the surrounding soil with a sand/cement backfill sufficient to cover the cable, and the trench is backfilled with granular material. When ground movement is sufficient to fracture the grout, cable deformation occurs that can be monitored with a TDR cable tester (O'Connor and Dowding, 1999). As mentioned above, the magnitude of each TDR reflection will increase as progressive ground movement continues to deform the cable. This technology has been effective for monitoring subsurface movement over several abandoned mines *(4-8)*.

IMPLEMENTATION

Rationale for Cable Locations, Orientations, and Lengths

The TDR monitoring system is intended to provide early detection of precursor cumulative deformation events and the rates of deformation. The intent is also to provide a method to detect events during the night or other times of nonattendance by employees. Cable locations, orientations and lengths were chosen by a team of USG personnel who have extensive experience with the operating mine conditions, behavior of the rock mass, and historical subsidence activity at this site. Vertical and inclined installations (Figure 3) make it possible to detect precursor movement as fracturing and caving propagate toward the surface. Installing cable in trenches provides the capability of monitoring over large lateral extents. Borehole and trench locations indicated by the triangle symbol in Figure 4 were chosen to be (a) in proximity of known subsided or caved areas, (b) in areas over shallow underground workings and (c) in other strategic locations to provide an early warning of ground movements.

Cables 331 (TDR1), 332 (TDR3), and TDR2 were installed to test for mass movement over known underground mined void locations and subsiding areas. Locations 331 and 332 are important for monitoring mass rock movement underneath SR 91 and at the intersection of SR 91 with CR 745. TDR-2 was installed over a backfilled subsidence sinkhole.

Cable 311 is a vertical borehole installation to test for movement near a mineshaft. Cables 312, 314, 321, and 322 are installed in trenches. These particular installations represent a transition to direct monitoring of ground movement below the waste-rock pile as it is being built-up. Cables 321 and 312 are strategically located over the "boulder zone" mine workings where there are large, interconnected stopes that are partially backfilled as well as a second mine shaft. Cables 322 and 314 are located over the "footwall" mine workings (Figure 2). All the TDR cables in this series were deliberately placed along lines corresponding with the most intensely undermined areas.

Given the requirement for public safety along SR91, the renewed activity within sinkholes in this area, and the anticipated increase in construction activity, several locations were added to the monitoring network. Eight cables (333, 334, 336, 341, 342, 343, 344, and 345) were added in inclined holes, and two cables (335 and 346) were added in trenches along the highway. Furthermore two cables (324 and 325) were added along the haul road that crosses the central portion of the site.

Figure 6 Data acquisition system. The solar panel trickle-charges the battery. The phone modem is hard-wired to a phone line.

Automated Monitoring

The site is divided into sectors and each cable within a sector extends to a data acquisition system (DAS) for that sector. Each cable is connected to a coaxial multiplexer installed within an enclosure such as the one shown in Figure 6. The multiplexer and TDR cable tester are controlled by a datalogger. The datalogger is also attached to a storage module and modem so each DAS is accessible remotely via phone connection.

The datalogger cycles over each cable once every three hours and stores the measurements. The datalogger is programmed to compare the current waveform point-by-point against the stored baseline waveform for each cable. If the system detects a change from the baseline value that exceeds the alarm threshold, the datalogger initiates a phone call to assigned responsible personnel.

Movement Detected

Movement has been detected and been the source of alarm calls. This movement has been associated with (a) ongoing mine subsidence along SR91 and (b) movement associated with construction activity. The movement associated with construction activity is related to truck traffic and placement of excavated rock in the former board plant area.

Ongoing Subsidence along SR91

As mentioned previously, there has been historical subsidence and it has been monitored by precise level surveys along SR91 as well as through the mine property. These measurements are the basis for current thinking about the mode of rock deformation. In addition to isolated sinkholes, there has been a subsidence trough developing along the roadway (Figure 7). The trough is continuing to develop in the vicinity of a chimney-type subsidence feature in SR-91 that developed in 1936 and reactivated in 1977 (near location 332 in Figure 4). The measured total subsidence of the trough since 1994 is 155 mm (0.55 feet). In November 1998, the rate of movement decreased from 0.063 to 0.031 mm/day (0.075 to 0.037 ft/yr) in response to backfilling of mine stopes.

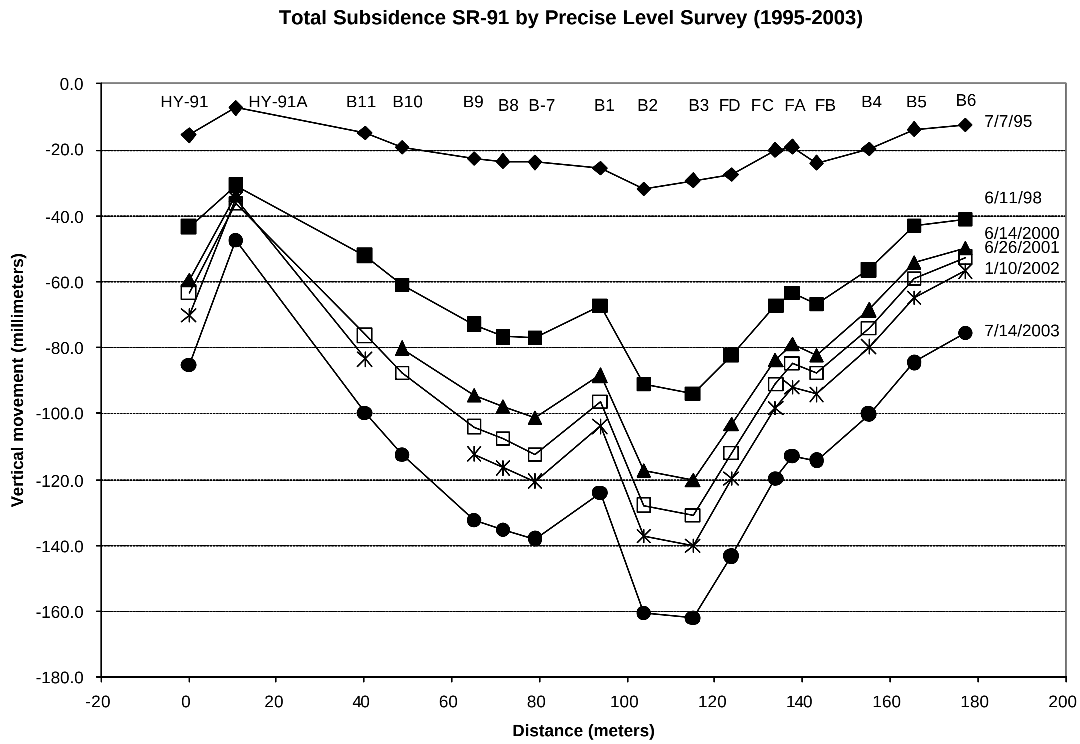

Figure 7 Precision level survey profile along S.R. 91

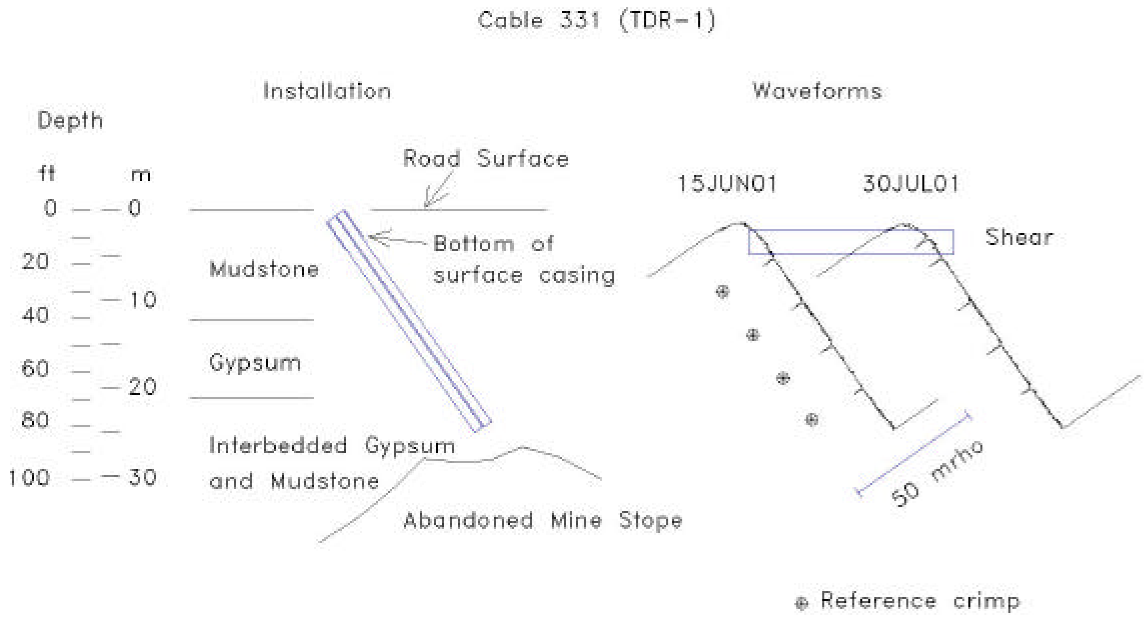

Figure 8 Installation details, boring log, and TDR waveforms for cable 331.

At location 331 the cable was progressively sheared at a measured depth of 3 m (10 ft) which corresponds with the bottom of the surface casing that was left in place (Figure 8). Cable deformation occurred at an essentially constant rate of 0.018 mm/day (Figure 9) during the period from July 2001 to January 2002. There was accelerated movement corresponding with heavy rains on July 27 and 30, 2001. This accelerated movement occurred again in late August when there was another major precipitation event. This correlation of rainfall to accelerated subsidence is important because it may be an indication as to how the mined voids will respond when the mine dewatering pumps are turned off and the workings are allowed to flood. Comparison of precipitation and dewatering records has shown that there is a hydrogeological connection between surface runoff of rainfall and infiltration of water into the underground workings.

Cable 332 is in the location of the historic sinkhole along SR91. Shear displacement in cable 332 at a depth of 10 m (30 ft) began 3 to 5 days after the heavy rain event at Plasterco on August 27, 2001. During the period from 9/4/01 to 2/1/02, deformation occurred at a rate of 0.007 mm/day, then increased to 0.023 mm/day until 5/10/02 when it accelerated. On 5/24/02 this cable was sheared off. It was replaced by drilling an adjacent angled hole and installing a cable on June 14, 2001. Movement has continued at this location at a depth of 2.5 m (8 ft). The rate of deformation has been 0.011 mm/day with accelerated movement of 0.097 mm/day in August 2002 and 0.378 mm/day in October 2002.

Shear displacement has occurred at several locations along cable 335, but it is concentrated in the area of cable 342. Cable 335 is installed in a trench along SR91 and cable 342 is installed in an inclined hole beneath SR91. The deformation in cable 342 has been occurring at a depth of 21 m (70 ft) within interbedded gypsum and mudstone where circulation was lost during drilling. The rate of movement has been 0.011 mm/day. The precise level survey data does not show anomalous activity or accelerated downward movement along SR-91. Although the root cause of the deformation in the cables is speculative, the waveform shapes are consistent with ground movement, the area is known to be undermined, and the rate of movement from precise level measurements is consistent with the rate indicated by TDR measurements.

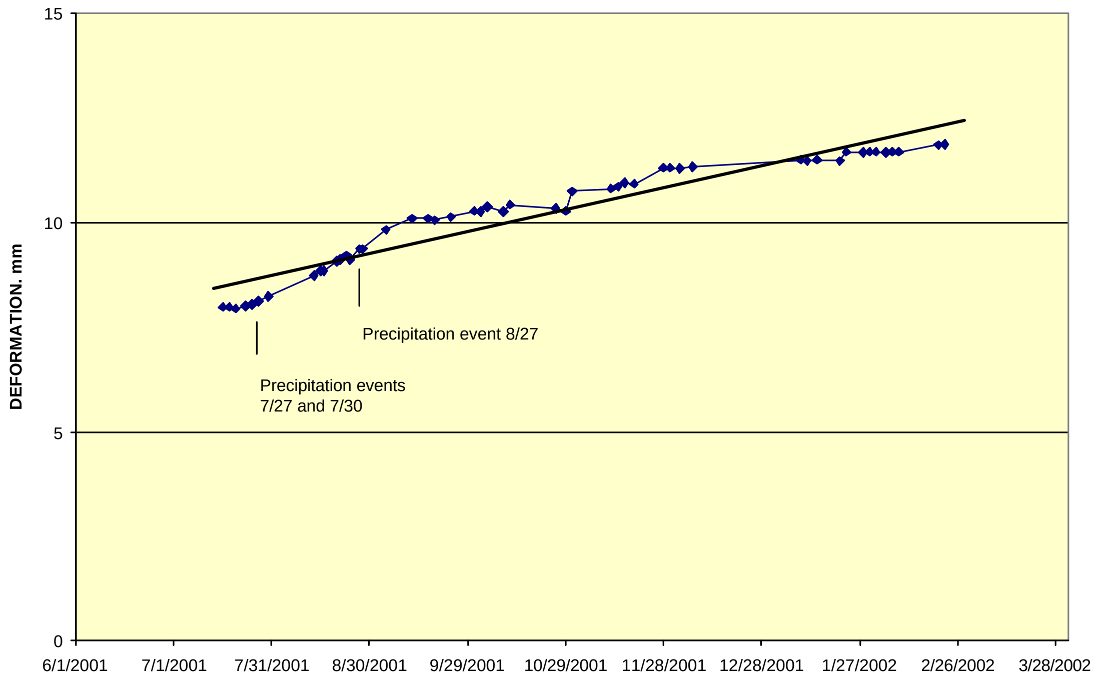

Figure 9 Displacement time history for movement at a depth of 3 m (10ft) in cable 331.

Haul Road Truck Traffic

Concentrated surface loading has occurred along the construction haul roads traversed by 64,000 kg (80 t) trucks moving the excavated rock. The volume of soil being stressed is limited to a depth of approximately 1m (3 ft) and a lateral extent of on the order of 3 m (10 ft) outside the wheel ruts. Along the haul road, deeper movement has not been detected and cables outside this volume have not been deformed.

Trucks moving along the haul road at the north end of the site caused deformation and shearing of the “lead” portion of cables 345 and 346 in trenches at a depth of 1 m (3 ft) below the haul road. When an excavation was made to rehabilitate the cable, it appeared that the deformation occurred due to the “soft” subgrade beneath the haul road.

The sensitivity of TDR technology is limited by the geology and the distance between the physical location where movement occurs and the location of the grouted coaxial cable. For example, a sinkhole developed along the haul that crosses the central portion of the site. The sinkhole is located about 7.5 m (25 feet) from cable 325 which is installed in a trench near the haul road. The sinkhole was about 3 m (10 ft) in diameter and 1 m (3 ft) deep. However the magnitude of movement, if any, beneath cable 325 has not been large enough to fracture the grout and there has not been any detectable deformation of the cable.

Movement below Waste Rock Pile

Rock excavation and waste rock placement began in May 2003, and the waste rock pile reached a height of approximately 20 m (60 ft) in October 2003. Cables 312 and 322, installed in trenches beneath the pile, began deforming in July 2003. Cable 312 was sheared off at 112 m (366 ft) from DAS1 on 10/13/03, and cable 322 was sheared off at 230 m (753 ft) from DAS2 on 10/15/03. Both cables were sheared at locations that correspond with historic mine subsidence sinkholes. In response to this movement, the contractor is now placing waste rock in another area outside the mine workings.

Response to Alarm Calls and System Checks

A default value for the alarm threshold was established by experience on previous projects *(4)*. This value was set independently for each cable and it was adjusted periodically as responsible personnel gain experience with the system and changing site conditions. For example, it would be temporarily increased for a cable during periods when noise levels on that cable are high and then lowered as conditions stabilized. The objective is to keep the threshold as low as possible to maximize sensitivity to changes from the baseline waveform.

In response to alarm calls from the TDR monitoring systems installed at Plasterco, it is vital to isolate the cause. It is necessary to download and analyze TDR data files to determine if the alarm condition is associated with ground movement and the rate at which movement is occurring. Based on this information, it is possible to make an informed decision when talking with personnel on site about the appropriate plan of action. Once it is determined that the alarm call was triggered by a condition that is persistent, it is typical to validate the condition using on-site manual interrogation of the coaxial cable, identify the physical location, conduct a visual assessment, and develop a plan of action.

The summary of alarm calls in Table 2 is presented to illustrate how alarm calls can continue over a period of time. Often this was deliberate to verify that a condition is not intermittent and there is a high probability that it is associated with cable deformation. Alarm calls will continue to be received until the alarm condition is rectified or the alarm is deliberately terminated. For example, in Dec 2002 there were problems with cold weather impacting the system so alarms were created that were not associated with movement. In March 2003, there were problems with a connector on cable 324. However, at the same time there was deformation occurring on cables 345 and 346 so each alarm condition had to be identified and appropriate action taken for each of the three cables.

TABLE 2 TDR Alarm Activity Log

Period	**Alarm Calls**		
	Total	**Due to Deformation**	
JUN 2002	5	0	0
JUL 2002	17	4	24%
AUG 2002	14	2	14%
SEPT 2002	7	0	0
OCT 2002	2	2	100%
NOV 2002	0	0	0
DEC 2002	52	0	0
JAN 2003	6	0	0
FEB 2003	0	0	0
MAR 2003	108	49	45%
APR 2003	42	3	7%

SUMMARY AND CONCLUSIONS

This project demonstrates the capability of real time monitoring of ground movement over inactive or abandoned underground mines over a wide area utilizing TDR technology. TDR measurements are an integral component of the response action plan. Furthermore, regular evaluation of the TDR measurements makes it possible to have proactive rather than reactive subsidence monitoring.

Cables are automatically interrogated once every three hours, checked against a baseline for changes, and data is stored. A call back alarm is activated when a change exceeds the action level. Responding to an alarm call is very different from proactively downloading and plotting data to evaluate changes. The response is emotionally charged, and discipline is required to rationally and objectively assess the situation. This requires experienced, knowledgeable personnel.

TDR is a direct indicator of mass movement and does not allow for much subjectivity. TDR technology has made it possible to perform continuous remote monitoring of subsurface movement in critical areas. Alarm calls have occurred in response to actual ground movement and also in response to other sources. As project personnel became familiar with the system response and developed a comfort level with the technology it became easier to develop operating procedures for responding to alarm calls.

The warning capability provided by this technology has not only been important for public safety along SR91 but also for the safety of personnel involved in construction of the new road alignment. Cable deformation which occurred in response to placement of the waste rock pile has provided a warning that portions of the pile are becoming unstable as the underlying rock deforms and traffic is diverted from identified areas.

It has been found that the rate of subsurface deformation measured using TDR cables installed in boreholes and trenches is consistent with the rate of surface subsidence based on precise level surveys. Periods of heavy rainfall are indicated to accelerate rock mass movement.

A limitation of the technology is that the cables only indicate ground movement that deforms the cable. A case in point is the sinkhole that developed near the haul road on the central portion of the site. This sinkhole was about 3 m (10 ft) in diameter and 1 m (3 ft) deep. Cable 325 in a trench 7.5 m (25 ft) away did not detect any movement of the ground.

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